Optimal Utilization of Grid-Connected PV -Wind-Fuel Cell Hybrid System

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Abstract— Future smart grids are becoming smarter by applying intelligent control techniques. In this paper, a hybrid energy system consisting of wind, photovoltaic and fuel cell designed to supply continuous power to the load. Wind and photovoltaic are the primary power sources of the system to take full advantage of renewable energy around us. The FC is used as a backup and long term storage system. For a stand-alone application, a battery is also used in the system as short term energy storage to supply fast transient and ripple power. In the proposed system, the different energy generating sources are integrated. Dynamic models for the main system components, namely, wind energy conversion system (WECS), PV energy conversion system (PVECS), fuel cell, power electronic interfacing circuits, hydrogen storage tank is developed. Solid Oxide Fuel Cell (SOFC) types of fuel cells has been modeled in this paper & also based on the dynamic component models, a simulation model for the proposed hybrid energy system has been developed using MATLAB Simulink. The overall power management strategy for coordinating the power flows among the different energy sources is presented also in this paper.

Key words: Renewable Energy Sources, DC/DC Boost Converter, DC/AC Inverter, Hybrid Energy System, Maximum Power Point Tracking (MPPT), PV Array, Squirrel Cage Induction Generator (SCIG), Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cell (SOFC)

I. INTRODUCTION

The ever-increasing demand for conventional energy sources like coal, natural gas and crude oil is driving society towards the research and development of alternate energy sources. [1] The non-conventional energy sources are usually clean, renewable, small and flexible, and have become important elements in a diversified set of alternative generation sources. The integration of these energy sources to form a hybrid system is an excellent option for distributed energy production.

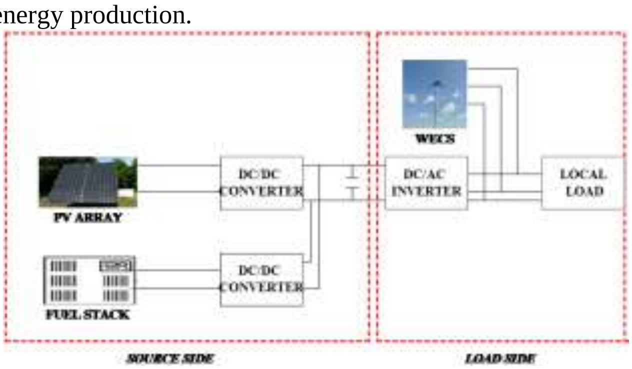


Fig. 1: Proposed System Block Diagram

1) Over the last few years, electrical energy consumption has continually grown and investment in the Transmission and Distribution (T&D) infrastructure has correspondingly declined. So that the power grid is under stress, resulting in poor reliability and higher energy costs. However, system reliability is vital and cannot be compromised. To overcome this problem, future grid operators are moving away from radial distribution systems towards networked grids; this will degrade controllability of the distribution network. Therefore, there is a great need to evolve the traditional grid to become a smart grid by applying intelligent control techniques. [2]
2) Figure (1) shows hybrid wind, photovoltaic and fuel cell generating system. The wind and photovoltaic are used as primary energy sources, while the fuel cell is used as secondary or back-up energy source. A simple control method tracks the maximum power from the wind energy source without measuring the wind or generator speed, which is very useful for actual small size wind turbines. The same control principle is applied to track maximum power point of the photovoltaic system without sensing the irradiance level and temperature. The fuel cell is also controlled using a dc-dc converter to supply the deficit power when the primary energy sources cannot meet the load demand. In the complete absence of power from the wind and photovoltaic sources the fuel cell supplies its full rated power of 50 kW.
3) The system studied in this paper comprises of a 1000 kW wind turbine generator, 50 kW photovoltaic arrays and 50 kW fuel cell. Individual step-up dc-dc converter is used to control each of the three sources. The individual dc-dc converters of are in turn connected to a single PWM voltage source inverter, which holds the output voltages of all the converters at a fixed value by balancing input and output power of the dc links.

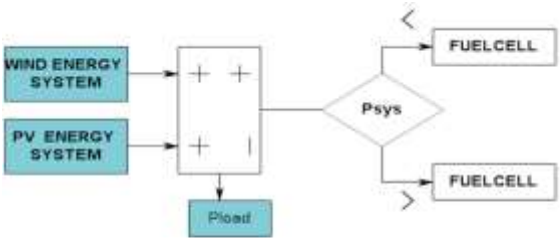


Fig. 2: Overall Power Management Strategy for the Hybrid Energy Generation System

– If P_{load} exceed the available power generated by PV (P_{pv}) and Wind (P_{wind}), the fuel cell (P_{fc}) will come into the action.

$$P_{load} = P_{wind} + P_{pv} + P_{fc},\ P_{sys}<0$$

– If wind and solar generation exceeds the load demand the surplus energy is again diverted towards the fuel cell.

$$P_{fc} = P_{wind} + P_{pv} - P_{load},\ P_{sys}>0$$

- If the wind and solar generation equals the load demand, then the whole power generated by the renewable sources is injected to the load.

$$P_{load} = P_{wind} + P_{pv},\ P_{sys}=0$$

II. HYBRID SYSTEM DESCRIPTION

The proposed hybrid system consists of the following:

- A 50 kW photovoltaic array
- A 1000 kW wind turbine
- A 50 kW fuel cell

A. Modeling of Photovoltaic Energy System & simulation results

Photons of light with energy higher than the band-gap energy of PV material can make electrons in the material break free from atoms that hold them and create hole-electron pairs, as shown in Figure 3. These electrons, however, will soon fall back into holes causing charge carriers to disappear. If a nearby electric field is provided, those in the conduction band can be continuously swept away from holes toward a metallic contact where they will emerge as an electric current. The electric field within the semiconductor itself at the junction between two regions of crystals of different type, called a *p-n* junction [3].

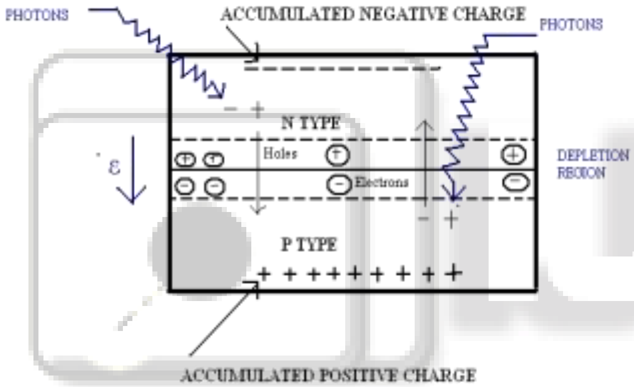
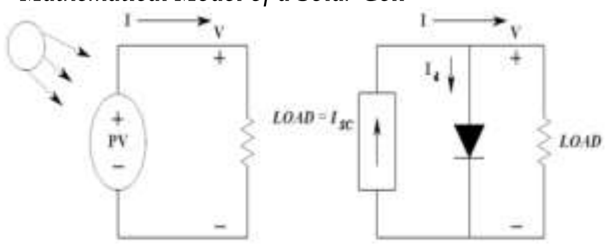


Fig. 3: Illustration of the p-n junction of PV cell showing hole-electron created by photons

1) Mathematical Model of a Solar Cell



$$i_d = I_o\left(e^{v_d/V_T} - 1\right)$$

$$i_{pv} = I_{sc} - i_d;$$

$$v_d = v_{pv}$$

Despite its simplicity, this model exhibits serious deficiencies:

- Its accuracy deteriorates at low irradiance levels.
- Parameters also vary with temperature and irradiance.

2) Modeling Equation of Solar Cell

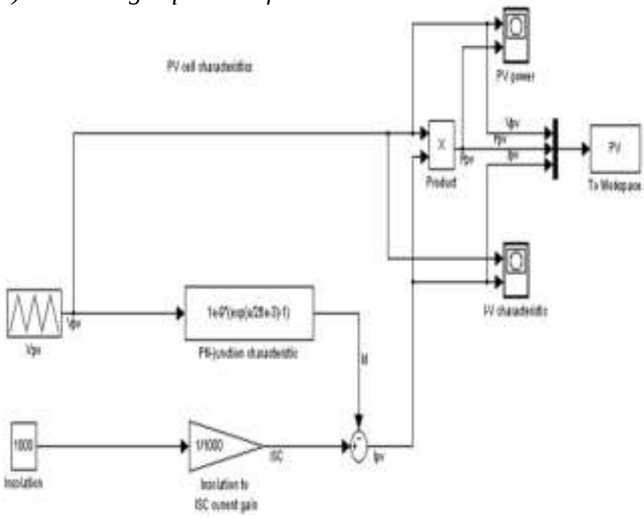


Fig. 4: Modeling Equation of Solar Cell

$$i_d = I_o\left(e^{v_d/V_T} - 1\right)$$

$$i_{pv} = I_{sc} - i_d;$$

$$v_d = v_{pv}$$

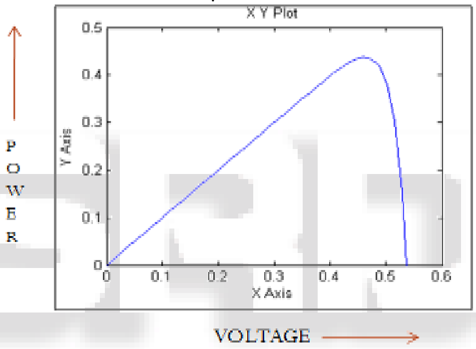


Fig. 5: P-V Curves

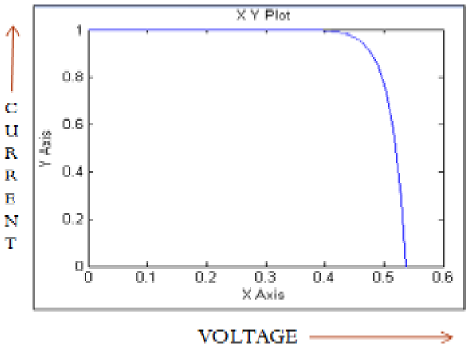


Fig. 6: I-V Curves

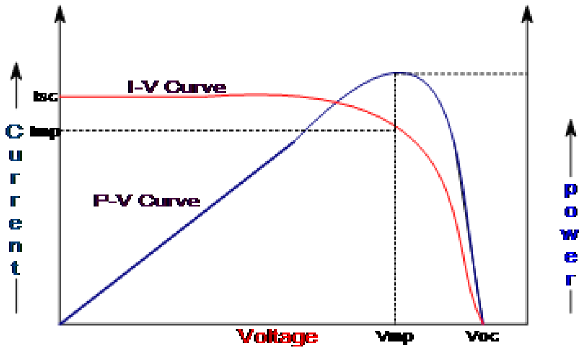
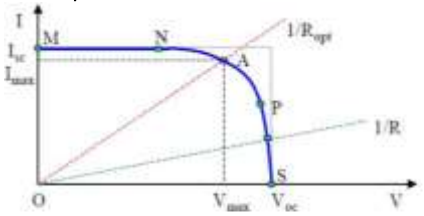


Fig. 7: V-I & P-V curve for PV cell

3) Parameters of Solar Cell



- Short circuit current: current procured when solar cell under short circuited situation.
- Open circuit voltage: can be obtained during night time where by the current produced zero.
- Max power point: states the max power dissipated at the load.(P_{max} /P_m)
- Max efficiency: ratio between incident light powers to max power.
- Fill factor: can be defined as how close the I-V curve can get close to be a square wave.

Ratio of maximum power that can be delivered to the load compared to I_{sc} and V_{oc}.

4) Modeling of PV Module

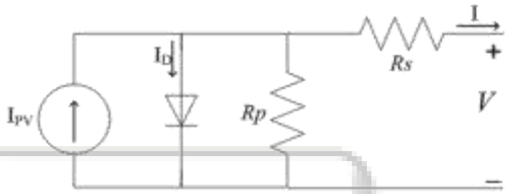


Fig. 8: Equivalent circuit of PV cell

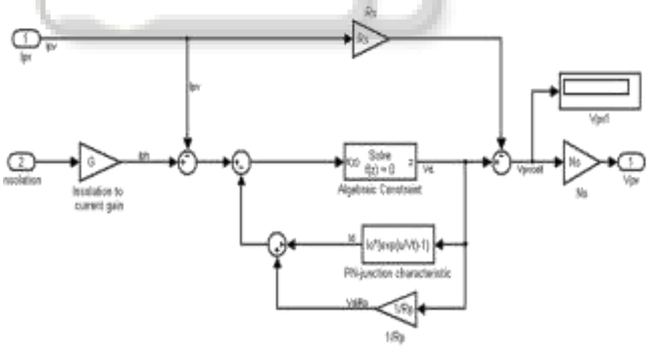
KCL:

$$I_{SC} - i_D - \frac{V_D}{R_P} - I_{pv} = 0;$$

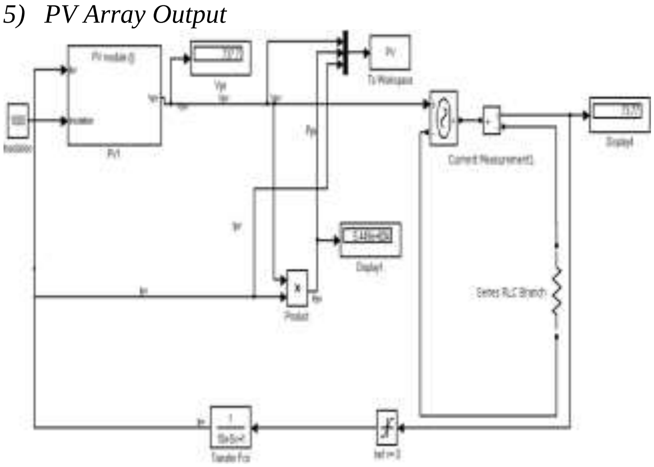
$$i_d = I_o\left(e^{V_d/V_t} - 1\right)$$

KVL;

$$V_{pvcell} = V_D - R_s I_{pv}$$



5) PV Array Output



Data Sheet Values

- I_{sc} = 87.2A
  V_{oc} = 888V
  I_r = 79.2A
  V_r= 704V
- V= I*R
  888 = 87.2 R
  R = 10.18 Ω

a) 1000W/m^2

RESISTANCE	VOLTAGE	POWER	CURRENT
10	737.7	54.49	73.77

b) 800W/m^2

RESISTANCE	VOLTAGE	POWER	CURRENT
10	655.7	43.08	65.57

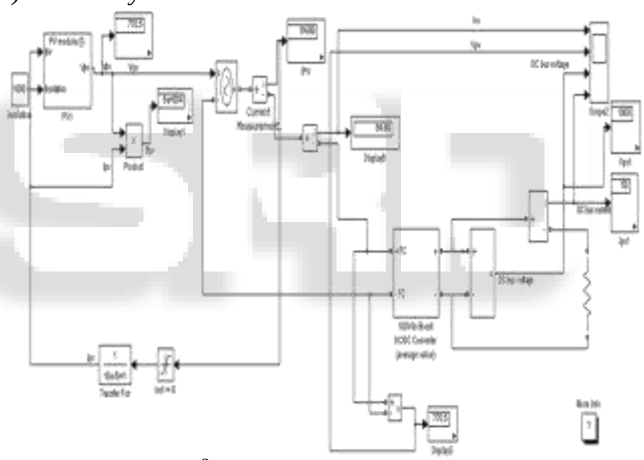
c) 600W/m^2

RESISTANCE	VOLTAGE	POWER	CURRENT
10	500.6	24.99	50.06

d) 200W/m^2

RESISTANCE	VOLTAGE	POWER	CURRENT
10	166.1	2765 W	16.61

6) PV Array Connected to Dc-Dc Converter

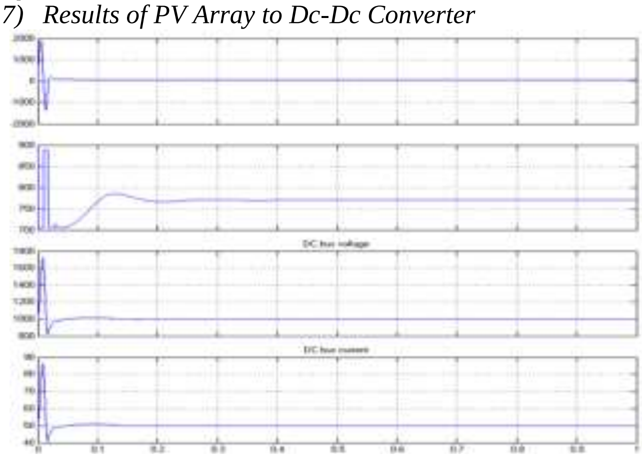


a) 1000W/m^2

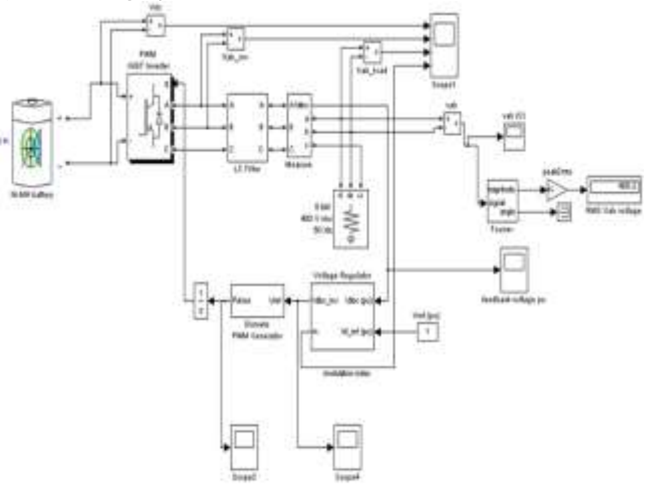
INPUT
V_{pv} = 770.5 v
I_{pv} = 64.89 A
P_{pv} = 50Kw

OUTPUT
V_{pv} = 1000 v
I_{pv} = 50 A

7) Results of PV Array to Dc-Dc Converter

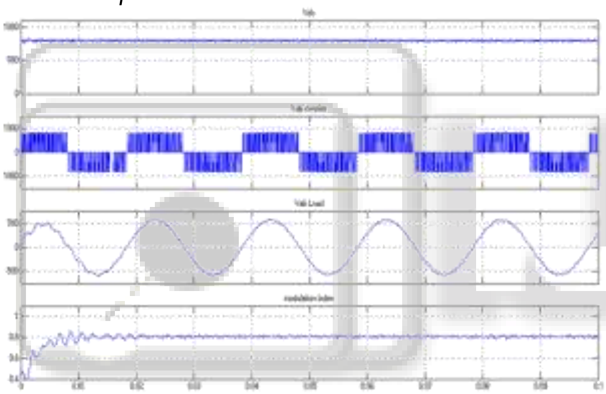


8) Modeling of Inverter



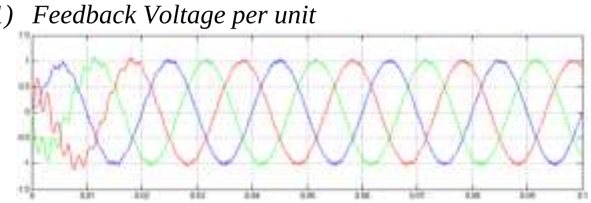
- The load voltage is regulated at 1 Per Unit (400 V RMS) by a PI voltage regulator using abc to dq and dq to abc transformations.
- The first output of the voltage regulator is a vector containing the three modulating signals used by the PMW Generator to generate the pulses.
- The second output returns the modulation index.

9) Results of Inverter

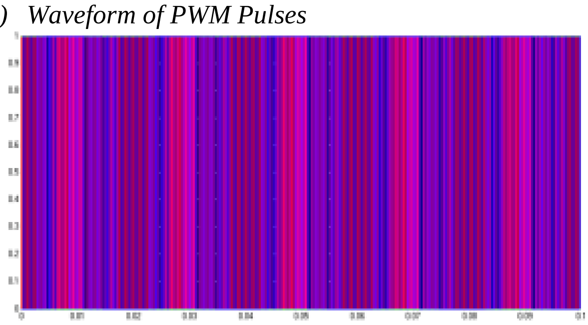


10) Difference between V_{abc} & V_d

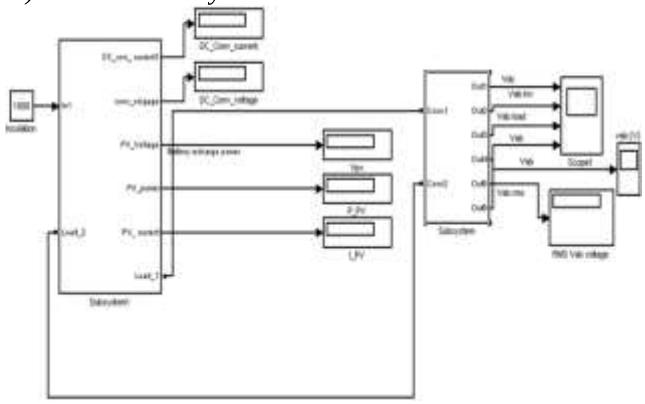
11) Feedback Voltage per unit



12) Waveform of PWM Pulses

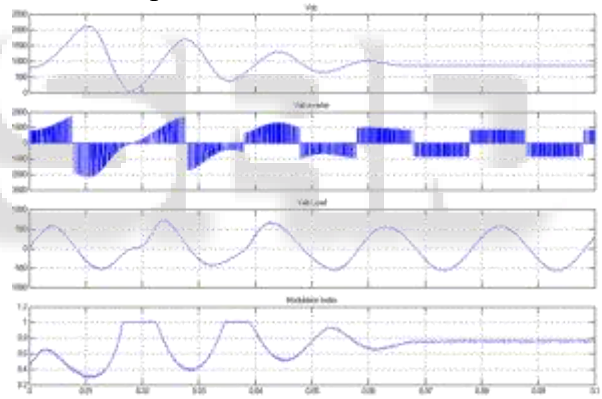


13) Photovoltaic System Connected Without MPPT



a) Parameter Values:
- DC Converter current: 48.31
- DC converter voltage: 856.4
- PV voltage (V_{pv}):834.6
- PV current (I_{pv}):51.31
- Load 1: DC bus current
- Load 2: DC bus voltage
- RMS V_{ab} voltage: 400.1

V_{dc}=800v
$V_{ab.inv}$=860v
V_{ab}=560.8v
M.I=0.76
RMS Vab voltage=400.1



It becomes very necessary to cope up with the variation in the input DC voltage. So as to overcome this unbalanced condition it is connected through the voltage regulator to achieve the balanced sinususoidal AC output voltage. Here the park transformation is used to for the voltage regulation. Inverter is operated with a PWM strategy i.e sine PWM under the feedback control to realize the desired output waveform.

Output of the regulator is then given to the discrete PWM generator by comparing the sinusoidal reference signal with the triangular carrier leading to the generation of pulses for the gate of the inverter.

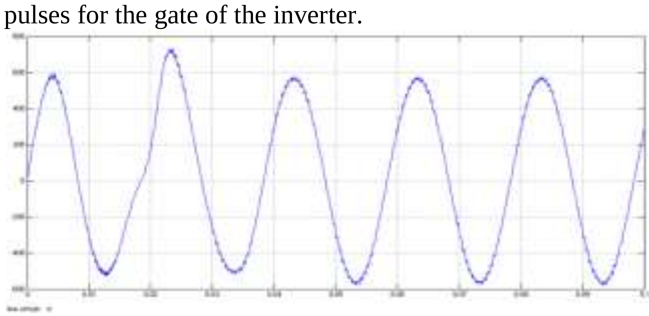
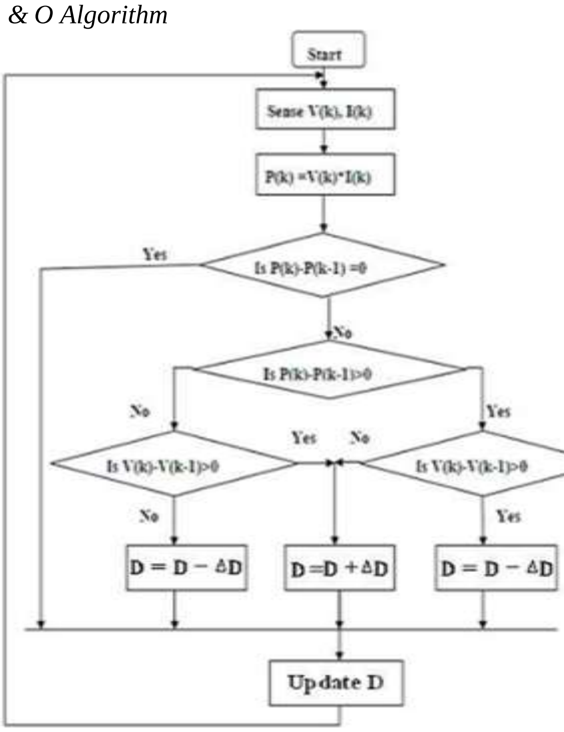
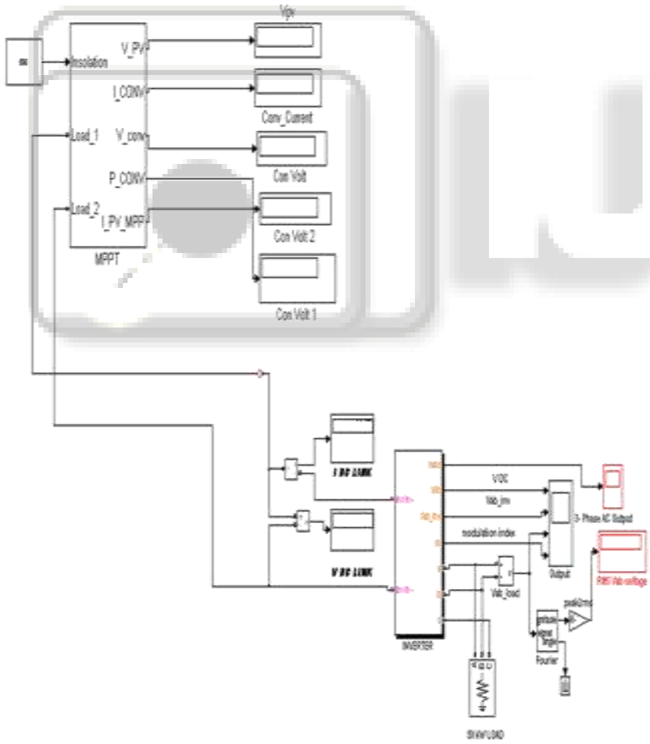


Fig. 9: Waveform OF V_{ab}

14) Photovoltaic System Connected With MPPT Technique P & O Algorithm



15) Photovoltaic System using with MPPT Technique



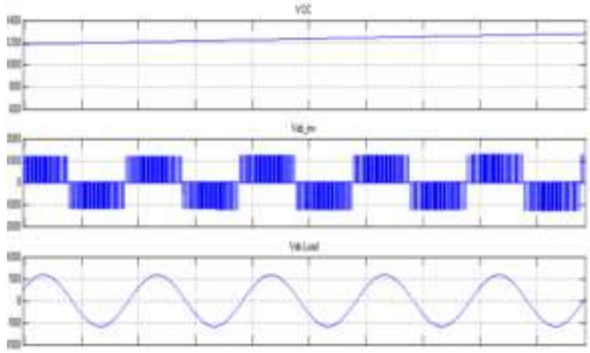
P&O algorithm is based on the calculation of the PV array output power and the power change by sensing both the PV current and voltage. The controller operates periodically by comparing the present value of the power output with the previous value to determine the change on the solar array voltage or current. If the magnitude of power is increasing, the perturbation will continue in the same direction in the next cycle, otherwise the perturbation direction is reversed. By using the MPPT method, perturb and observe, the output voltage can take values lower or bigger than V_{max}, therefore, a step down and step up chopper should be used.

16) MPPT Parameters Obtained Values

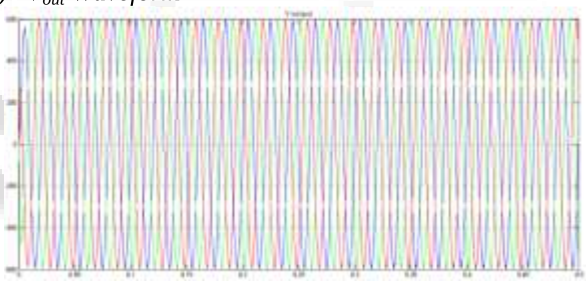
INSOLATION	Vpv	Ipv	D	Vcon	Icon	power	Vab rms
1000	642.3	78	0.529	1281	36.71	5.01E+04	415.2
900	636.6	71	0.553	1346	31.88	4.52E+04	415.2
800	637.1	63	0.566	1395	27.31	4.01E+04	415
700	661	56.8	0.5711	1431	23.39	3.50E+04	415.3
600	722.8	30	0.2	857.8	24.73	2.16E+04	415.3
500	695.1	38.8	0.5781	1466	16.22	2.25E+04	415.1
400	696	30.2	0.4617	1158	16.28	1.92E+04	418.8

Table 1: Ttabular representation of the implemented MPPT algorithm

17) Simulation Results PV Module with MPPT Technique



18) V_{out} Waveform



Conclusion can be drawn from the PV module results

The main aim of such an algorithm is to always ascend the power curve in order to achieve the maximum power Output from the PV cell. In this way, we always make the solar panel operate at a point that delivers maximum power. If an MPPT system is not implemented, the load connected to the panel is always constant, and it may not operate at maximum power point. Hence, it will not be trapping the maximum power available from the panel.

B. A Modeling of Wind Energy System & Simulation Results

Wind power is the conversion of wind energy into a suitable form of energy, such as using wind turbines to generate electricity, windmills for mechanical power, wind pumps for water pumping, or sails to propel ships. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind power, as an alternative to fossil fuels, is abundant, renewable, widely spread, clean, and produces no greenhouse gas emissions during operation. Wind power is the world‘s rapid growing source of energy.

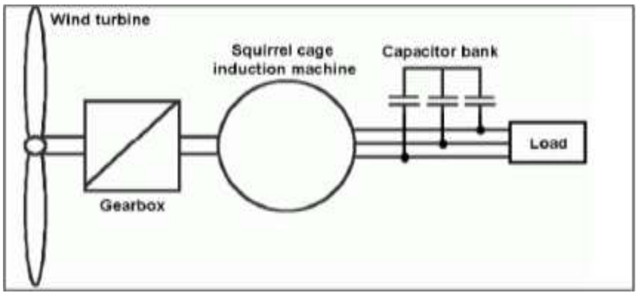
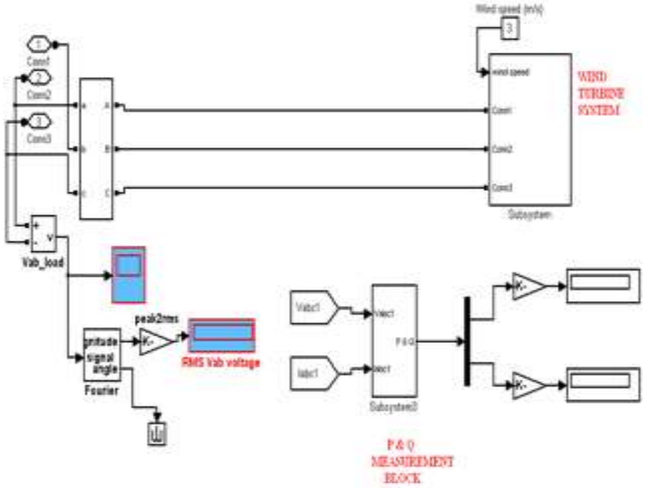


Fig. 10: squirrel cage induction generator (SCIG)

1) Wind Turbine System and Its Characteristics



Wind Speed m/s	p	q
12	345.2	8.289
11	269.2	26.89
10	201.9	39.5
9	144.7	47.44
8	92.83	52.48
7	50.06	55.1
6	15.41	56.22
5	-0.7394	56.44
4	-0.7394	56.44
3	-0.7394	56.44
2	-0.7394	56.44

Table 2: P & Q Measurement Block

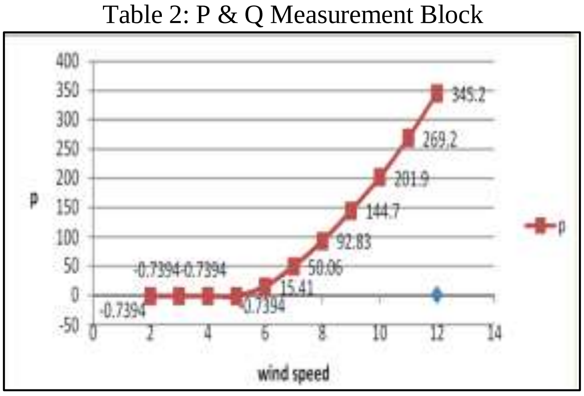


Fig. 12: speed v/s power

The all the values except the wind speed are in per unit and a typical fixed speed wind turbine with characteristics is shown in the tabular form was simulated and figure (12) represents the mechanical power (in pu) for several wind speeds.

– As the amount of power generated varies, the slip and the rotor speed of the SCIG induction generator also varies.
– These rotor speed variation are however very small approximately 1-2%.
– SCIG always consumes the reactive power. so the capacitors will try to compensate to the reactive to achieve the power factor nearer to unity.
– It is one of the most important properties that the generator will increase or decrease its speed slightly if the torque varies. This means that it will less wear and tear on gearbox.

C. Modeling of Fuel Cell Energy Storage System & & Simulation Results

Fuel cells based DG system is considered an alternative to centralized power plants due to their non-polluting nature, high efficiency, flexible modular structure, safety and reliability. At present, they are under extensive research investigation as the power source of the future, due to their characteristics. A fuel cell converts chemical energy directly to electrical energy through an electrochemical process. As opposed to a conventional storage cell, it can work as long as the fuel is supplied to it. There are many motivations in developing this method of energy generation and it needs further development to have a realistic system analysis combining various subsystems and components.

Among different types of fuel cells, proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC) are likely to be used in DG applications.

1) Basics of a Fuel Cell

The basic components of a typical fuel cell include two electrodes, an anode and cathode where the reactions take place. An electrolyte is sandwiched between anode and the cathode which allows the ions to cross over, while blocking the electrons. The electrolyte also allows the ions that are formed to cross-over to the other electrode, which happens because of the tendency of charged particles migrating to regions of lower electrochemical energy. The electrical energy is produced when the electrons traverse the external circuit, flowing from the anode to the cathode. The end products of a fuel cell are heat and electricity, which make them suitable for CHP (Combined Heat and Power) applications. The most commonly used fuel in a fuel cell is hydrogen and the oxidant is usually oxygen and the product of chemical reaction is water which is produced either at the cathode or at the anode, depending on the type of fuel cell used.

2) Solid Oxide Fuel Cell (SOFC)

The main reasons why the SOFC has been given precedence over other fuel cell are as follows:

– SOFCs are suitable for stationary power applications with step load changes.
– They provide higher system efficiency and higher power density
– The design of SOFCs is simpler than a fuel cell based on liquid electrolytes.
– The exhaust heat in case of SOFC can be utilized for co-generation application in industries.
– Internal reforming of natural gas reduces the cost considerably.

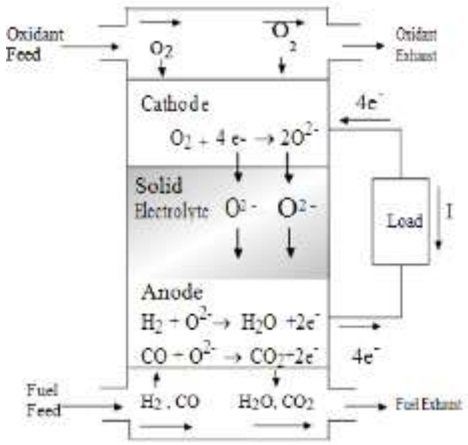


Fig. 13: Basic Electrochemistry of an SOFC

- Since an SOFC operates at a high temperature (500^{o}C to 1000^{o}C), it has high reactant activities which helps in reduction of activation polarization, thus increasing the cell efficiency.
- SOFCs are flexible in the choice of fuel such as carbon-based fuels, like natural gas.

3) Mathematical Model of SOFC

The following assumptions are made in developing the mathematical model of fuel cell stack:

- Fuel cell is fed with hydrogen and oxygen.
- The gases considered are ideal, that is, their chemical and physical properties are not co-related to the pressure.
- Nernst equation is applicable.
- Fuel cell temperature is stable at all times.
- The electrode channels are small enough that pressure drop across them is negligible.
- The ratio of pressures between the inside and outside of the electrode channels is sufficient to consider choked flow.
- Ohmic, activation, and concentration losses are considered.

The main equations describing the slow dynamics of a SOFC can be written as follows:

$$Vfc = No\left[Eo + \frac{RT}{2F}\ln\left[\frac{pH_2\, pO_2{}^{.5}}{pH_2O}\right]\right] - rI_{fc}$$

$$P_{ref} = V_{fc} * I_{ref} \quad \frac{dI_{fc}}{dt} = \frac{1}{T_e}\left[-I_{fc} + I_{ref}\right]$$

$$\frac{dq_{H_2}^{in}}{dt} = \frac{1}{T_f}\left[-q_{H_2}^{in} + \frac{2k_r}{U_{opt}} I_{fc}\right]$$

$$\frac{dP_{H_2}}{dt} = \frac{1}{\tau_{H_2}}\left[-P_{H_2} + \frac{1}{K_{H_2}}\left[q_{H_2}^{in} - 2k_r I_{fc}\right]\right]$$

$$\frac{dp_{O2}}{dt} = \frac{1}{\tau O_2}\left[-P_{O_2} + \frac{1}{K_{O_2}}\left[\frac{1}{r_{H_2O}} Q_{H_2}^{in} - 2k_r I_{fc}\right]\right]$$

$$\frac{dp_{H_2O}}{dt} = \frac{1}{\tau_{H_2O}}\left[-P_{H_2O} + \frac{2K_r I_{fc}}{K_{H_2O}}\right]$$

$$\tau O_2 = \text{response time for oxygen}$$

$$\tau H_2 = \text{response time for hydrogen}$$

$$\tau HO_2 = \text{response time for water}$$

Where:

V_{fc}= operating DC voltage (v)
E_o= standard reversible cell potential (v)
r= internal resistance of the stack(s)
I=stack current (A)
N_o= no. of cells in the stack
R_s=Universal gas constant (Jol/mol K)
T=stack temperature (k)
F=faradays constant(C/mol)
qH_2=fuel flow (mol/sec)
qO_2=oxygen flow (mol/sec)
kH_2=molar constant for hydrogen (kmol/sec atm)
kO_2=molar constant for oxygen (kmol/sec atm)
kH_2O=molar constant for water (kmol/sec atm)
U_{opt} – Optimum fuel utilization
rHO – Ratio of hydrogen to oxygen
K_r – Constant (kmol/s A)
P_{ref} – Reference power (kW)

4) Simulation model results Of SOFC

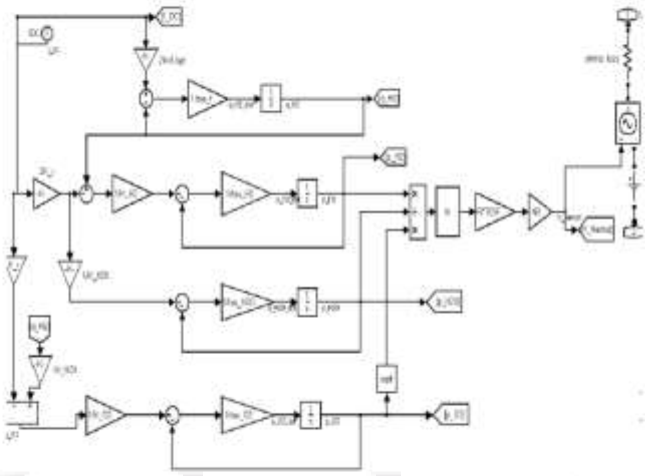
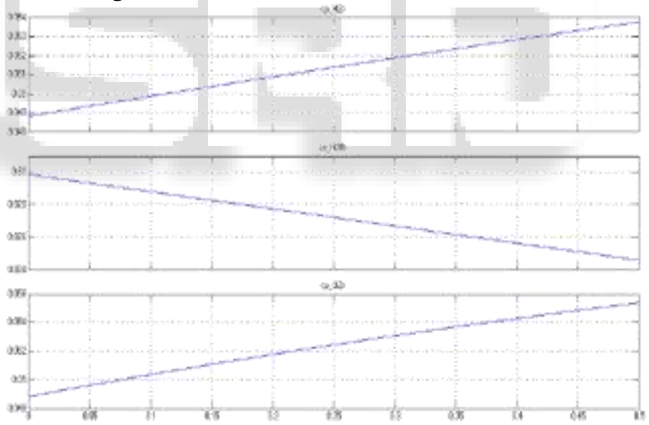


Fig. 14: Fuel cell MATLAB/Simulink model



From the above waveforms it has been shown that the fuel utilization ranging from 0.8 to 0.9 yields better performance and prevents overused and underused fuel conditions. Considering the specified fuel condition, U_f>0.9 can cause permanent damge to the cell because of the fuel starvation and U_f<0.7 leads to higher cell voltage rapidly. The optimum utilization factor assumed for this model is 0.85.The fuel utilization can be set at this value by regulating the input fuel flow depending on the real output recorded in the fuel cell output current is given as:

$$q_{H2}^{in} = \frac{2KrIfc}{0.85}$$

The power output of fuel cell system is the product of stack current and voltage. The Various dynamic behaviours of the developed fuel cell SOFC model with step change in reference input have been obtained.

D. Final Module "Integration of PV/Wind/Fuel cell Energy Generation System

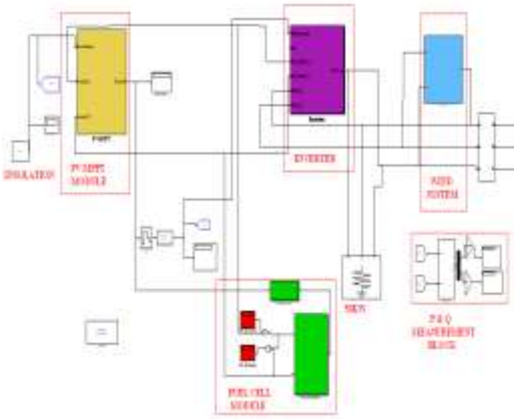


Fig. 15: PV/Fuel Cell/Wind Energy Generation Module

The integration of the all the three sources of generation energy is more economical to supply to the load by this hybrid combination of the energy system because it doesn't need the fuel cell to do work whole day. It could effectively regulate the output power properly and so as its transients were damped very quickly.

1) Tabular Representation of PV/Wind/Fuel Cell System

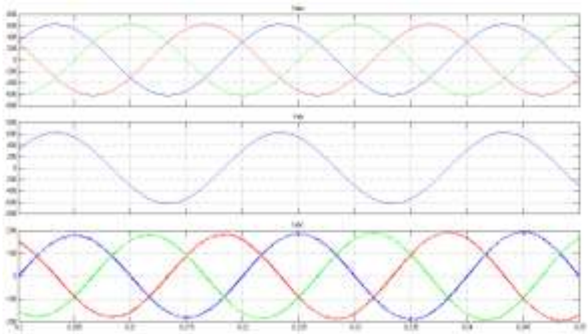
WIND	INSOLATIONS	MPPT PV				FUEL CELL				P	Q
		Vpv	Vcon	Icon	power	DUTY cycle	Vfc	Ifc	Vdc		
12m/s	1000	630.5	675.3	78	4.92E+04	0.875	675.3	40	419.9	-420.4	-10.16
	800	594.3	674.6	69.4	4.12E+04	0.829	674.5	45	419.1	-410.2	-10.8
	600	600.2	675.5	51	3.06E+04	0.85	675.4	40	419.8	-396.6	-10.1
	400	600.2	675.5	51	1.97E+04	0.849	675.4	40	419.8	-384.4	-10.9
10m/s	1000	630.5	675.3	78	4.92E+04	0.875	675.3	40	419.9	-277.1	-41.37
	800	594.3	674.6	69.4	4.12E+04	0.829	674.5	45	419.1	-266.8	-41.31
	600	600.2	675.5	51	3.06E+04	0.85	675.4	40	419.8	-253.3	-41.31
	400	590.9	675.6	33.4	1.97E+04	0.849	675.6	40	419.8	-241.4	-41.31
8m/s	1000	630.5	675.3	78	4.92E+04	0.875	675.3	40	419.9	-168	-54.35
	800	594.3	674.5	69.4	4.12E+04	0.829	674.5	45	419.1	-157.7	-54.29
	600	600.3	675.5	51	3.06E+04	0.85	675.4	40	419.8	-144.2	-54.29
	400	590.9	675.6	33.4	1.97E+04	0.849	675.6	40	419.8	-132	-54.27
6m/s	1000	630.5	675.3	78	4.92E+04	0.875	675.3	40	419.9	-90.58	-58.09
	800	594.3	674.6	69.4	4.12E+04	0.829	674.5	45	419.1	-80.35	-58.03
	600	600.2	675.5	51	3.06E+04	0.85	675.4	40	419.8	-66.35	-58.03
	400	590.9	675.6	33.4	1.97E+04	0.849	675.6	40	419.8	-54.63	553.02
4m/s	1000	630.5	675.3	78	4.92E+04	0.875	675.3	40	419.9	-74.4	-58.31
	800	594.3	674.6	69.4	4.12E+04	0.829	674.5	45	419.1	-64.18	-58.25
	600	600.2	675.5	51	3.06E+04	0.85	675.4	40	419.8	-50.63	-58.25
	400	590.9	675.6	33.4	1.97E+04	0.849	675.6	40	419.8	-38.45	-58.23

Table 3: Constant Wind Speed, Varying Insolation

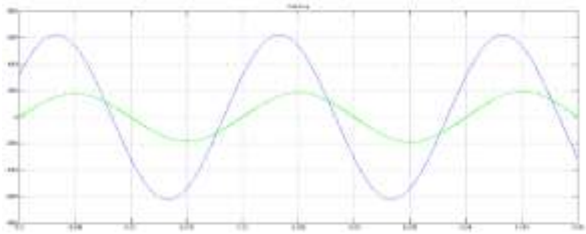
a) Waveforms:

UNDER WIND SPEED: 12m/s and INSOLATION : 1000w/m^2

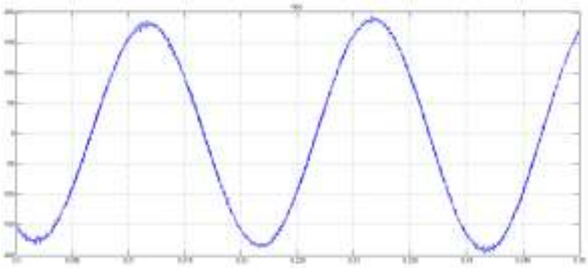
1) V_{abc}, V_{ab}, I_{abc}



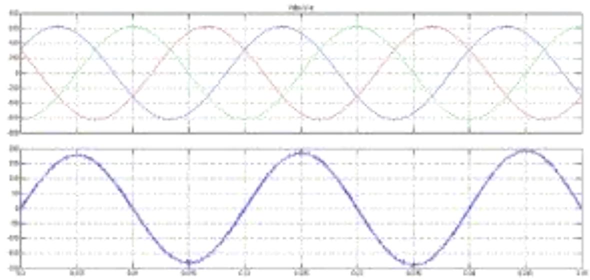
2) V_{ab} & I_a



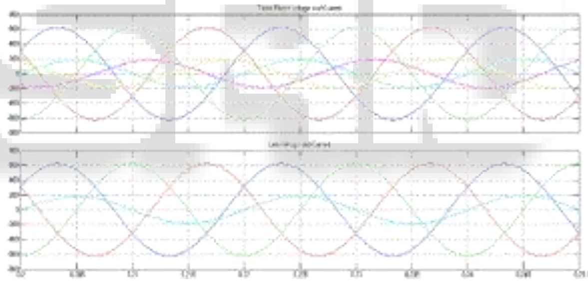
3) I_{abc}



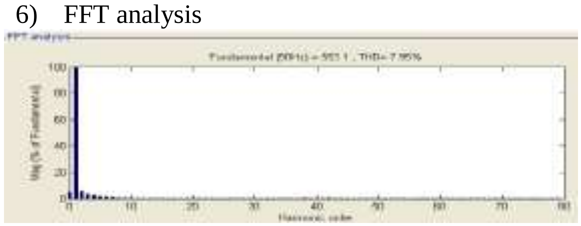
4) V_{abc} & I_{abc}



5) Three phase voltage and current, Line voltage and current

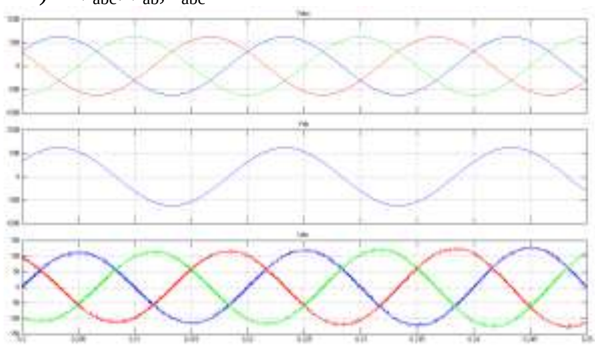


6) FFT analysis

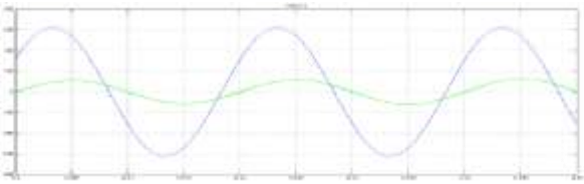


b) Waveforms under Wind Speed: 12m/s and INSOLATION: 400w/m^2

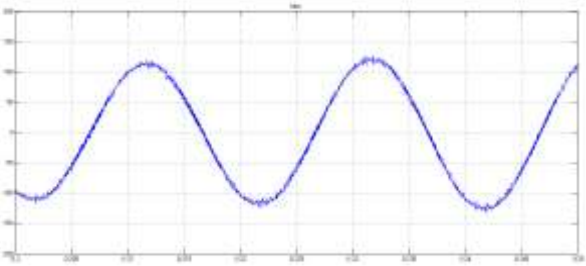
1) V_{abc}.V_{ab}, I_{abc}



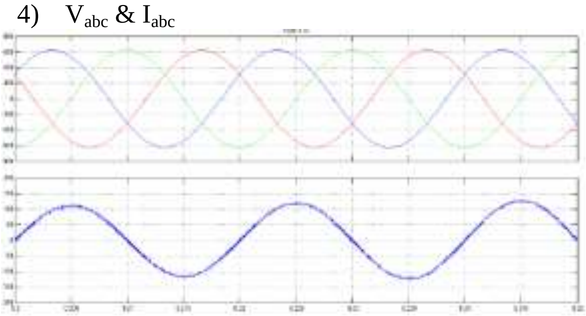
2) V_{ab} & I_a



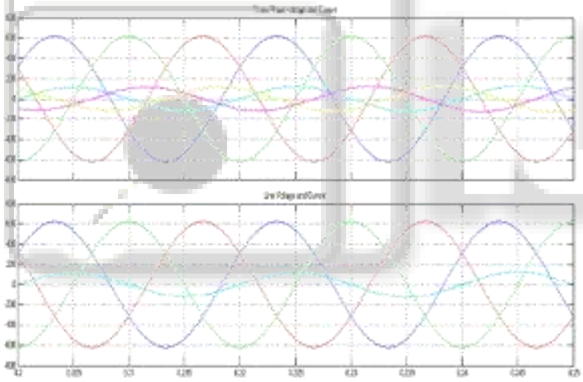
3) I_{abc}



4) V_{abc} & I_{abc}



5) Three phase voltage and current, Line voltage and current



III. CONCLUSION

The paper presents on modeling and control of a hybrid PV/wind/FC alternative energy system with MPPT. The wind and photovoltaic systems are controlled to operate at their point of maximum power under all operating conditions. The designed power management strategy has been modeled and simulated in MATLAB/Simulink software and then undergone with the Integration of all the three sources of generation of energy i.e PV/WIND/FC system which shows the effectiveness in the system performance.

Environmentally friendly and sustainable alternative energy systems will play more important roles in the future electricity supply.

The advantage of this proposed system is that it is highly reliable because of the three different sources of generation of energy are connected are parallel, because it doesn't require the fuel cell to work all day long.

Simulation results show the effectiveness of the overall power management strategy and the feasibility of the proposed hybrid alternative energy system.

The overall system provides a continuous power output across the grid without considering load variation and environmental changes. Therefore the power fluctuation of the hybrid system is less compared to individual system and has been completely achieved using the fuel cell system.

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